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Evaluation of crop water stress index for LEPA irrigated corn

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Abstract This study was designed to evaluate the crop water stress index (CWSI) for low-energy precision application (LEPA) irrigated corn (*Zea mays* L.) grown on slowly-permeable Pullman clay loam soil (fine, mixed, Torrertic Paleustoll) during the 1992 growing season at Bushland, Tex. The effects of six different irrigation levels (100%, 80%, 60%, 40%, 20%, and 0% replenishment of soil water depleted from the 1.5-m soil profile depth) on corn yields and the resulting CWSI were investigated. Irrigations were applied in 25 mm increments to maintain the soil water in the 100% treatment within 60–80% of the "plant extractable soil water" using LEPA technology, which wets alternate furrows only. The 1992 growing season was slightly wetter than normal. Thus, irrigation water use was less than normal, but the corn dry matter and grain yield were still significantly increased by irrigation. The yield, water use, and water use efficiency of fully irrigated corn were 1.246 kg/m^2, 786 mm, and 1.34 kg/m^3, respectively. CWSI was calculated from measurements of infrared canopy temperatures, ambient air temperatures, and vapor pressure deficit values for the six irrigation levels. A "non-water-stressed baseline" equation for corn was developed using the diurnal infrared canopy temperature measurements as $T_c - T_a = 1.06 - 2.56$ VPD, where T_c was the canopy temperature (°C), Ta was the air temperature (°C) and VPD was the vapor pressure deficit (kPa). Trends in CWSI values were consistent with the soil water contents induced by the deficit irrigations. Both the dry matter and grain yields decreased with increased soil water deficit. Minimal yield reductions were observed at a threshold CWSI value of 0.33 or less for corn. The CWSI was useful for evaluating crop water stress in corn and should be a valuable tool to assist irrigation decision making together with soil water measurements and/or evapotranspiration models.

Key words Crop water stress index · Crop production · Evapotranspiration · Irrigation · Low-energy precision application

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Introduction

Irrigation is an increasingly important practice for sustainable agriculture in the southern Great Plains region of the United States as well as in other arid and semiarid regions of the world. The southern Great Plains region encompasses the High Plains of Texas, New Mexico, Oklahoma, southwestern Kansas, and southeastern Colorado. Irrigation water supplies are mainly from groundwater sources (Ogallala aquifer) that are being depleted (Kromm and White 1992; Opie 1993). Musick et al. (1990) evaluated the irrigation trends in the Texas High Plains and reported a 28% decline in the irrigated area from 1974 to 1989 with a 44% corresponding decline in the groundwater use during this period. However, in the Texas High Plains, over the past 8–9 years this trend has reversed. The irrigated area is now about 1.8 million ha (TWDB 1996) and has stabilized after a slight increase.

Corn, cotton, winter wheat, and grain sorghum are the major crops on the Texas High Plains, but of these crops, corn has the greatest irrigation requirement (Musick et al. 1990). Musick et al. (1988) reported that sprinkler irrigation was used on 37% of the total irrigated land area in this region in 1984 and that sprinkler irrigation remained stable despite a decrease in irrigated land, which can be attributed to the high cost of energy and declining well capacities and lower commodity prices (Gardner et al. 1996; Vaux et al. 1996).

Center-pivot systems permit reduced water applications per unit land area and sustained irrigated production in this region (Musick et al. 1990). This region has large wind speeds and low energy precision application (LEPA) irrigation, developed by Lyle and Bordovsky (1981), which can reduce application losses to droplet evaporation and runoff by use of the integral furrow dikes that are part of LEPA. Lyle and Bordovsky (1983) reported that LEPA was superior to sprinkler and furrow methods in terms of application efficiency, water use efficiency, and energy savings potential. They also reported advantages for alternate furrow LEPA compared to every-row LEPA besides the obvious reduction in hardware costs. Alternate furrow LEPA, the most common type in use currently, results in every other furrow being irrigated. This can enhance rainfall infiltration into the dry furrow, but it could impose a greater soil water deficit in a portion of the root zone. Currently, LEPA devices are commercially available to operate in bubble and chemigation (inverted spray) modes as well as in double-ended sock mode (Fangmeier et al. 1990).

LEPA irrigation of corn and sorghum was evaluated on Pullman clay loam soil at Bushland, Tex., during 1989 and 1990 by Howell et al. (1991), and both crops had similar yields under LEPA irrigation compared with the more traditional methods such as graded furrow and sprinkler. LEPA enhanced cotton lint yields and provided efficient use of limited water on the Southern High Plains region of Texas (Bordovsky et al.1992) using deficit, high frequency irrigation. LEPA was also evaluated at Garden City, Kan. by Spurgeon and Makens (1992) for corn and soybean, and they recommended furrow diking for all LEPA systems. Lyle and Bordovosky (1995) concluded that substantial water savings could be achieved by irrigating corn frequently (3–6 day intervals) using LEPA without a yield decline. Howell et al. (1995) indicated that corn yields under LEPA irrigation declined in proportion to reduced water use when deficiently irrigated.

Irrigation scheduling methods are generally based on measurement of soil water content or meteorological parameters for modeling or computing evapotranspiration. Irrigation scheduling based upon crop water status should be more advantageous since crops respond to both the soil and aerial environment (evaporative demand). Plant stress measurements with hand-held infrared thermometers (IRT) have become increasingly popular in the last 10–15 years (Hatfield 1990). Idso et al. (1981) presented an empirical approach for quantifying stress by determining "non-water-stressed baselines" for crops. They developed linear relationships for canopy-air temperature difference ($T_c - T_a$) versus vapor pressure deficit (VPD). Jackson et al. (1981) introduced the theoretical method for calculating the crop water stress index (CWSI). This approach requires net radiation and aerodynamic and crop canopy resistance to water vapor transport in addition to temperature and vapor pressure terms required by the empirical method. Some reviews of canopy temperature and crop water stress research can be found in articles by Jackson et al. (1988) and Gardner et al. (1992a, 1992b).

Major shortcomings of the CWSI technique for irrigation scheduling reported by Stockle and Dugas (1992) include the difficulty in measuring T_c of row crops in early stages of growth and the fact that it allows determination of irrigation timing but not amounts. In addition, T_c measurements are highly sensitive to the view angle of the sensor and its relation to the solar zenith angle (Fuchs 1990) and azimuth angle (Nielsen et al. 1984). Therefore, standardization and consistency in the procedures are important (Gardner et al. 1992b; Stockle and Dugas 1992). Despite the above-mentioned shortcomings of the technique, irrigation scheduling based on T_c measurements with IRTs appears to be promising for some crops (Nielsen and Gardner 1987; Nielsen 1990).

Clawson and Blad (1982) utilized infrared thermometry for scheduling irrigation for corn in Nebraska. They used T_c variation as an indication of water stress. Idso (1982) developed non-water-stressed baselines for various crops including corn. Nielsen and Gardner (1987) reported the results from their study on irrigation scheduling of corn with CWSI in Colorado and concluded that the IRT should become an increasingly important tool in irrigation scheduling in order to reduce irrigation costs. Braunsworth and Mack (1989) evaluated the relationship between CWSI and evapotranspiration (ET) and yield of sweet corn at Corvallis, Ore. and stated that seasonal average CWSI values were closely related to the seasonal ET deficit and yield deficit. Keener and Kircher (1983) pointed out potential limitations of the CWSI in humid regions with the lower evaporative demand and smaller T_c differences for corn.

The primary objectives of this study were as follows: (1) to evaluate crop water stress development using IRTs for alternate row LEPA irrigated corn; (2) to develop empirical CWSI parameters (non-water-stressed baseline and fully stressed baseline) for LEPA irrigated corn; and (3) to evaluate water use and water use efficiency of corn in relation to the CWSI.

Materials and methods

This study was conducted at the USDA-ARS Conservation and Production Research Laboratory at Bushland, Tex., (35°11′N lat., 102°06′W long.; 1170 m MSL) during 1992. Howell et al. (1995) presented the irrigation aspects of the 2-year study (1992 and 1993 seasons), and this work examined the crop water deficits that were measured only in 1992. The soil at this site is classified as Pullman clay loam (fine, mixed, thermic Torrertic Paleustoll) (Taylor et al. 1963; Unger and Pringle 1981) which is described as slowly permeable because of a dense B22 horizon about 0.3–0.5 m below the surface. The plant available water holding capacity within the top 2.0 m of the profile is approximately 200 mm. A calcareous layer at about 1.5 m depth limits significant rooting and water extraction below this depth. This soil is common to more than 1.2 million ha of land in this region and about one third of the sprinkler irrigated area in the Texas High Plains (Musick et al. 1988). The field slope is less than 0.3%.

Table 1 Cropping, phenological development stages, agronomic practices data for the experiment

Parameter	Date	Day of year
Planting	21 April	112
Harvesting	6 October	280
Emergence	30 April	121
Tasseling	11 July	193
Silking	13 July	195
Physiological maturity	28 September	272
Pest control		
Atrazine herbicide	23 April	114
Accent herbicide	19 May	140
Lorsban insecticide	1 August	214
Ambush insecticide	18 August	230
Fertility		
Pre-experiment	6.6 g(N)/m2	
Preplant (uniform	22.4 g(P)/m2	
(application)	25 March	187
Treatment applications	12.0 g(N)/m2	
(LEPA socks mode)	15 July and 21 July 3.0 g(N)/m2	197, 203
Irrigations		
Uniform rate (spray mode 25 mm)	23 April	114
Uniform rate (bubble mode 25 mm)	11 May	132
Treatment irrigations	7, 9, 15, 21 July	189, 191, 197, 203
(25 mm in LEPA socks	25, 31 July	207, 213,
mode)	10, 12, 14 August	223, 225, 227

A three-span center pivot sprinkler system (Lockwood) that was 135 m in length was used. LEPA heads (Senninger Quad-Spray IV) were used along with internal pressure regulators (41 kPa). LEPA heads were located about 0.4 m above the ground, spaced 1.52 m apart, centered between two rows, equipped with a one-quarter-turn valve, and attached to flexible PVC hoses from the main pipeline. Nozzle sizes for each treatment (three LEPA drops per plot) were computed for each row based on its radius from the pivot point and for an irrigation supply capacity of 8.1 mm/day. Irrigation water was supplied from wells in the Ogallala aquifer pumped into an above-ground, lined reservoir. A centrifugal pump lifted and pressurized the water from the reservoir to the center-pivot system. An in-line totalizing water meter measured the total flow through the center-pivot sprinkler system.

The experimental design was a complete randomized block design with three replications. Plot lengths were 20% of the pivot circumference. The irrigation treatments were based on soil water depletion replenishments. A "control" treatment designated to receive 100% soil water depletion on a weekly basis was used to guide irrigation applications. The measured soil water depletion from this treatment was used as the basis of weekly irrigations applied to the treatments designated to receive 100%, 80%, 60%, 40%, and 20% of the control soil water depletion. In addition, a non-irrigated treatment (0% replenishment) was used; however, this treatment received irrigations for crop establishment. The control soil water depletion was based on the mean 1.5-m profile soil water content subtracted from 500 mm (0.333 m^3/m^3 mean volumetric soil water content), which was determined by prior experimentation and approximates to 90% of the field capacity for the Pullman clay loam, or about 80% or more of the plant extractable soil water. The soil water content was measured weekly in the three replications of the control treatment. Irrigations were applied to this treatment in 25-mm incremental applications to replenish the crop water use from the previous week. The remaining treatments were irrigated at the same frequency as the control treatment but with designated treatment amounts, which were achieved by sizing the LEPA nozzles for each plot for its desired treatment flow rate based on its radius from the pivot point (see Howell et al. 1995, for additional details).

Fertilizer applications were based on soil analysis recommendations. Nitrogen was applied as anhydrous ammonia (NH_3) preplant by ground application at a rate of 12.0 g (N)/m^2. Remaining nutrient requirements were applied by chemical injection using an injector pump (Inject-O-Meter model I-70) at the pump outlet with the irrigation water. The treatments received fertilizer in proportion to the irrigation water applied to the treatments. Pests (weeds, insects, and diseases) were uniformly controlled by ground and aerial applications when necessary according to recommendations.

Corn (Pioneer 3245) was planted in the 1992 growing season on a quadrant of the circularly tilled field. The plots were positioned around the center pivot (i.e., in circular rows) using 0.76 m spaced rows. Each plot had three LEPA applicators which applied water to alternate furrows, which were non-traffic furrows, of the six-row plot. Commercial farm equipment was used in all farming operations. Planting was done with a six-row planter (John Deere Max Emerge) with a seeding density of 7 seeds m^2. Furrow dikes were installed with a six-row drag-shovel, bump-wheel type diker (Roll-A-Cone) at intervals of approximately 3 m. The other agronomic practices are summarized in Table 1.

Yield was determined by hand harvesting the two adjacent center rows in each plot. The harvest area was 4.57 m^2 (two rows, each 3 m long). Plant stems were cut at the ground for a total dry matter sample; the number of plants in the sample was counted; and the ears were counted and removed from each sample and the remainder of the sample oven dried at 70 °C. The corn ears were also oven dried at 70 °C; seed mass was measured for 500 seed subsamples; and the yield components (seed number and seeds per ear) were computed using the ear densities, plant densities, and seed mass. Grain yields were converted to standard water content of 15.5% wet basis. Harvest index was based on the dry matter from one of the two harvested row segments, and computed as the ratio of dry grain yield to dry matter yield. The dry matter yield consisted of all above-ground plant materials (leaves, stems, tassels, shucks, cobs, and the grain) remaining at harvest.

T_c were measured with a hand-held IRT (Everest model 110), which has a field of view of 3° and detects radiation in the 8–14 μm waveband. The IRT was operated with the emissivity adjustment set at 0.98 and was compared frequently to an Everest blackbody standard to check the instrument performance. The T_c was recorded from the IRT as an analog signal by a datalogger (Omnidata polycorder model 516) which averaged five instantaneous readings taken from an oblique view angle to the crop rows to minimize the soil background in the field of view, first facing south then facing north. The mean T_c for each plot was determined as the average of ten readings. The IRT was hand-held at approximately 1.5 m above the ground surface until mid-June; thereafter, due to increased crop height, the IRT readings were taken from a pickup-truck tool box at a horizontal angle of 20°. The T_c measurements were made two to three times on weekdays between 1300 hours and 1500 hours Central Standard Time (CST) under clear skies or when the sun was unobscured by clouds. Diurnal measurements of T_c were taken on clear days following an irrigation or rainfall event and used for developing the non-water-stressed baseline for corn.

Dry- and wet-bulb temperatures were measured with an aspirated psychrometer at a height of 1.5 m in the open area adjacent to the experimental plots. The mean T_a was determined from the average of the dry-bulb temperature readings during the measurement period. The mean VPD was computed as the average of calculated instantaneous VPDs using the measured dry- and wet-bulb temperatures and the standard psychrometer equation (List 1971), with the barometric pressure assumed to be 89 kPa, which is appropriate for the Bushland elevation.

Daily weather parameters of maximum and minimum T_a, daily solar radiation, mean dew point temperature, mean 2 m wind speed, and daily precipitation were measured at an irrigated grass weather station located adjacent to the plots.

The empirical CWSI was calculated as:

$$\mathrm{CWSI} = [(T_c - T_a) - \mathrm{LL}]/(\mathrm{UL} - \mathrm{LL}) \tag{1}$$

where LL represents the non-water-stressed baseline (lower baseline) and UL represents the non-transpiring upper baseline. The UL

Table 2 Climatic data summary for the corn experiment contrasted to historical climate data from Bushland, Tex

Months	Max. air temp. °C	Min. air temp. °C	Mean dew point temp. °C	Mean solar radiation MJ/m^2	Mean 2-m wind speed m/s	Total rainfall mm
April	22	6	3	21.9	3.9	15
May	24	10	6	20.7	4.0	81
June	28	14	10	24.9	3.7	165
July	32	17	13	25.8	4.5	68
August	29	16	12	21.4	4.3	102
September	28	13	8	20.0	4.7	9
October	24	6	2	15.2	4.0	6
Historical climate data						
April	22	4		22.5		26
May	26	10		24.4		68
June	31	15		26.3		78
July	33	17		25.6		65
August	32	16		22.8		71
September	28	12		19.2		49
October	23	6		15.4		40

was estimated following the method described in Howell et al. (1986).

The water balance of each plot was determined by measuring the soil water contents at periodic intervals in each plot. The control treatment soil water contents (three plots) were measured weekly. Soil water contents in the other treatments were measured at emergence and then tri-weekly (21 days) until maturity.

Water use (ET) was estimated by water balance methods using soil water measured by the neutron method assuming no runoff (likely due to furrow dikes) and no deep percolation (less likely to be valid). Even though runoff and percolation could not be directly accounted, it is unlikely they were significant. A Campbell Pacific (model 502 HD) probe was used with 30-s integration and with 0.2-m increments from 0.2 m to a depth of 2.4 m. Soil water contents were computed from the measured count ratio using a local field calibration equation. A separate local, field calibration equation for the 0.3 m depth was used for the measurements at 0.2 m. Water use efficiency was computed as the ratio of dry grain to water use. Irrigation water use efficiency (IWUE) was computed as:

$$\mathrm{IWUE} = (\mathrm{GY}_i - \mathrm{GY}_0)/(I_i - I_0) \quad (2)$$

where IWUE is in kg/m^3 (kg of grain per unit water volume in m^3 which equals one g of grain per unit water mass in kg), GY is the dry grain yield in g/m^2, and I is the applied irrigation water in mm with the subscript i representing a treatment and 0 representing treatment T-00 (no seasonal irrigations).

Results and discussion

The 1992 growing season climatic conditions were typical of the conditions that prevail in the Southern High Plains. Table 2 summarizes the monthly climate data compared with the long-term mean climatic data for Bushland, Tex. The 1992 growing season temperatures were typical of long-term means at Bushland. However, the 1992 growing season (May–October) rainfall was 446 mm, which was about 12% above the long-term mean rainfall of 397 mm. Rainfall was particularly greater than normal in May and June; hence, no significant irrigation was required while the canopy was developing.

Table 3 Yield and yield component data for 1992

Treatment	Grain yield (kg/m^2)	Harvest index (kg/kg)	Dry matter yield (kg/m^2)	Kernel mass (mg/kernel)	Kernel numbers (no./m^2)	Kernels per ear (no./ear)
T-100	1.246 a	0.574	1.986 a	308	4386 a	716 a
T-80	1.236 a	0.568	1.879 a	318	4587 a	703 a
T-60	1.041 b	0.551	1.680 b	310	4054 ab	663 ab
T-40	0.972 bc	0.538	1.548 bc	330	3693 bc	522 bc
T-20	0.826 c	0.532	1.441 c	318	3135 c	474 c
T-00	0.603 d	0.505	0.934 d	301	2449 d	422 c
$\mathrm{LSD}_{0.05}$	0.061	ns	0.073	ns	258	60

Two uniform rate irrigation applications, 25 mm each, were made. The first application was made on day of year (DOY) 112, just after planting, and the other on DOY 132 after emergence, in the spray mode and the LEPA bubble mode, respectively. Irrigations were applied in the LEPA sock mode during the remainder of the growing season. Due to the start-stop nature of the electric powered center-pivot system and the high flow rates associated with LEPA, the furrow dikes and the sides of the beds themselves eroded considerably, and the storage capacity in the furrow was consequently reduced, even though only a single application was made in the bubble mode. The LEPA applicator was changed from the bubble to the sock mode after that one application. Lyle and Bordovsky (1983) used a wider row spacing (1.0-m spaced rows are more common with cotton) which avoids some of the problems we encountered with the 0.76 m spaced rows. Rainfall during May and the rapid growth of corn in May did not allow rediking of the furrows. The double-ended LEPA socks worked effectively throughout the study without causing any overtopping of furrows or dikes as long as applications were less than 25 mm.

Corn yields

Corn harvest data are presented in Table 3. Irrigation amounts, water use and water use efficiency data are summarized in Table 4. Corn grain yield was significantly increased by the irrigation level ($P<0.01$). Highest yield, averaging 1.246 kg/m^2, was measured for the T-100 treatment. Dry matter yields were also significantly different among the treatments and varied from 0.934 kg/m^2 for the T-00 to 1.986 kg/m^2 for the T-100 treatment. In addition, after tasseling, both the dry matter and leaf area index in T-100 treatment remained consistently greater than in T-60 and T-20 treatments (data in Howell et al. 1995). Harvest index (HI) ranged from 0.505 to 0.575 and was not significantly affected by any imposed treatments ($P<0.16$). Kernel mass ($P<0.86$) and the number of ears per plant ($P<0.06$) (data not shown) were not significantly different among the treatments. However, kernels per ear were influenced similarly to both the grain and dry matter

Table 4 Water use and water use efficiency data for 1992

Treatment	Seasonal irrigation (mm)	Soil water depletion (mm)	Water use (mm)	Water use efficiency (kg/m^3)	Irrigation water use efficiency (kg/m^3)
T-100	279	70	786 a	1.34 ab	2.13
T-80	228	72	737 b	1.42 a	2.63
T-60	178	79	695 c	1.27 ab	2.27
T-40	127	104	668 d	1.21 b	2.68
T-20	76	74	588 e	1.19 b	3.69
T-00	25	71	533 f	0.97 c	–
$LSD_{0.05}$		ns	13	0.09	

yields ($P<0.01$). Plant dry matter and plant grain yield were significantly increased by irrigation level ($P<0.01$). Number of kernels per plant was significantly different among the treatments studied (data not shown). The primary effect of water deficits on the corn grain yield was the reduction of kernel numbers, since late season rains reduced water deficit during grain filling and moderated the water stress effects on kernel mass.

Corn grain yields in this study were comparable with corn yields from previous experiments at Bushland using surface (Musick and Dusek 1980; Eck 1984; Eck 1986) and sprinkler irrigation (Howell et al. 1989). Howell et al. (1995) reported higher corn yields and water use in the 1993 season, but water use efficiency of the T-100 treatment was practically identical in both years. Using a validated CERES-maize corn growth simulation model for a 28-year period, Howell et al. (1989) estimated long-term mean non-stressed sprinkler irrigated corn yield at Bushland as 1.115 ± 0.223 kg/m^2. The maximum corn yield obtained from this experiment falls within this yield range. The corn grain yield remained a consistent proportion of dry matter yield whether expressed on an area basis or a single plant basis.

Crop water use

Soil water measurements with the neutron probe were begun on DOY 132 about a week from emergence, and the final readings were taken on DOY 275, 5 days prior to harvest. Thus, water balance data fairly represent the entire 1992 growing season as given in Table 4. The 1.5-m profile soil water contents are shown in Fig. 1 together with weekly irrigation applications and weekly rainfall totals. Experimental protocols were to measure soil water contents on Monday mornings (every week in T-100 if not prevented by rain) for irrigation scheduling. It was measured every 2nd or 3rd week, also on Monday, in the other treatments. Weekly irrigation decisions were made based upon the T-100 readings and the pre-set control level (500 mm for the 1.5-m profile). So the plotted soil water contents depicted in Fig. 1 represent the driest conditions (i.e., before the weekly irrigations). Irrigation plans were adjusted for rainfall. Total irrigation applications for corn varied from 25 mm for the T-00 to only 279 mm for the T-100 treatment. T-100 never reached a soil water depletion greater than 80 mm. This is about 42% of the available soil water according to Unger (1970) and Musick and Sletten (1966) for the Pullman soil. But Tolk et al. (1998) reported that on a Pullman soil, corn did not extract as much soil water as sorghum, so this depletion level for T-100 might have approached 60% of the plant available soil water, a level at which a yield reduction could be expected. So it is likely that T-100 experienced soil deficits large enough to impact yield, especially around DOY 215–225. These soil water deficits should explain why even T-100 had CWSI values over 0.2–0.5 occasionally. It remains possible that the alternate furrow LEPA irrigation wetting patterns affected crop rooting and soil water uptake that could have been detected with the CWSI measurements. Water use varied from 533 mm for the T-00 treatment to 786 mm for the T-100 treatment. Seasonal ET for corn at Bushland,

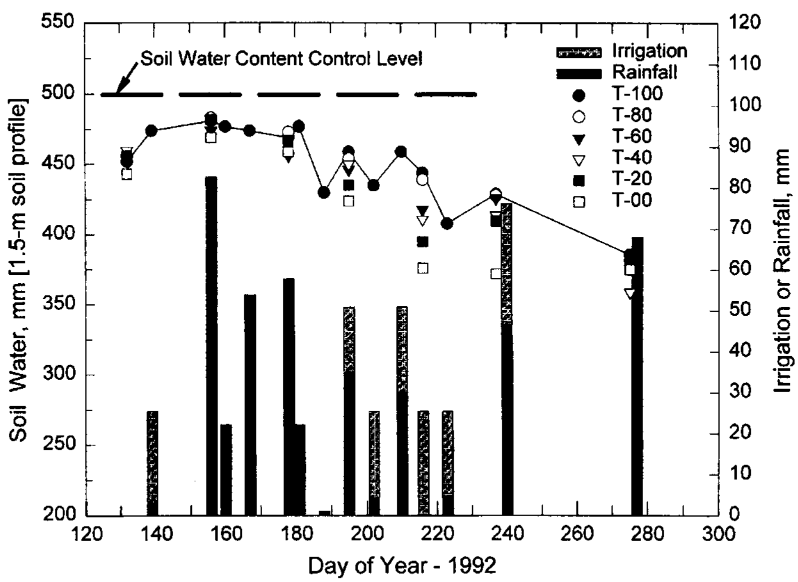


Fig. 1 Profile (1.5 m) soil water contents and weekly rainfall totals and weekly irrigations

Table 5 Corn "non-water-stressed" baselines; T_c canopy temperature in °C, T_a air temperature in °C, *VPD* vapor pressure deficit in kPa

Source	Equation
This work	$T_c - T_a = 1.06 - 2.56 \cdot \mathrm{VPD}$
Idso (1982)	$T_c - T_a = 3.11 - 1.97 \cdot \mathrm{VPD}$
Nielsen and Gardner (1987)	$T_c - T_a = 2.67 - 2.06 \cdot \mathrm{VPD}$
Stegman (1986)	$T_c - T_a = 0.84 - 1.93 \cdot \mathrm{VPD}$
Steele et al. (1994)	$T_c - T_a = 2.14 - 1.97 \cdot \mathrm{VPD}$

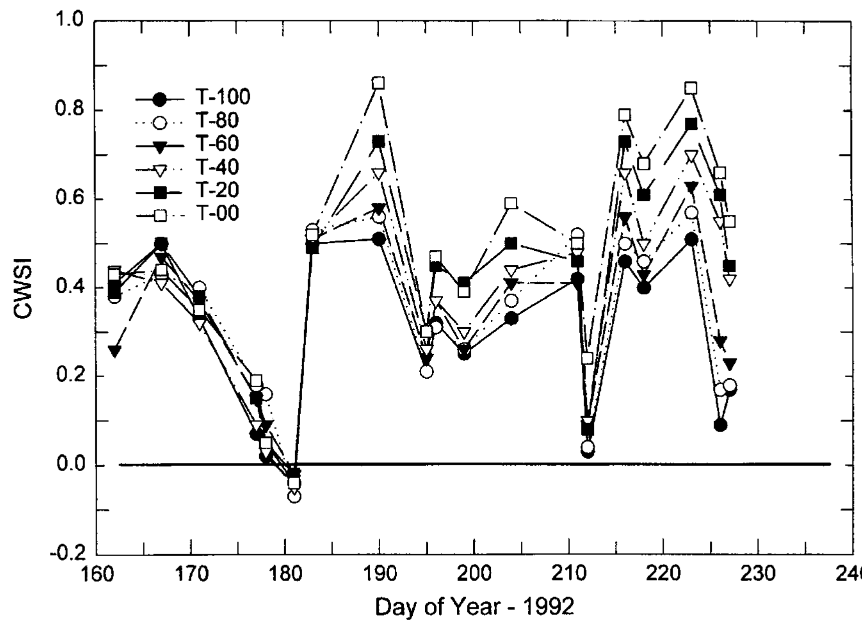
Tex., has been measured as high as 901 mm (Howell et al. 1997a, b) with weighing lysimeters. Water use of fully irrigated corn for the same location was reported as 838 mm (Howell et al. 1989) under sprinkler irrigation and as high as 956 mm (Howell et al. 1997c) under microirrigation (may have included some undetermined percolation losses). Further details of the water use and water use efficiency of LEPA irrigated corn in this study are found in (Howell et al. 1995). The 1992 water use rates were likely lower than normal during May and June because of the higher rainfall (more cloud cover and resulting higher humidities).

Water stress evaluations

The T_c measurements with the IRT were initiated on DOY 162 (11 June) and ended on DOY 227 (14 August). The measurements taken on DOY 181 (29 June) on the T-100 treatment plots were analyzed as a non-water-stressed baseline, since consecutive rainfalls received within the previous 2 weeks relieved water stress completely in all plots. The lower baseline was determined as $T_c - T_a = 1.06 - 2.56$ VPD with a r^2 of 0.934 and $S_{x/y}$ of 0.427 °C. The range in VPD was from 1.2 to 3.2 kPa, and T_c varied from 24 °C to 32 °C. The lower baseline equation obtained in this study differs somewhat from those given for corn from other studies (Table 5). Several factors can affect the baseline relation: (1) T_a, relative humidity measurement siting; (2) errors in determining the relative humidity (or whatever procedure used to compute VPD); (3) IRT calibration; (4) IRT aiming or field of view; (5) specific hybrid differences; and (6) other microclimate factors (like clouds or wind). This day was used because it was a clear day and winds were not extreme (mean half-hourly wind speeds during the observations ranged from 2 to 5 m/s) and because the soil water content was near the greatest measured during the season. Also, the crop had reached full ground cover to minimize soil background interferences. Our computed baseline intercept (1.06 °C) was within the range of the previous baselines (0.84 to 3.11 °C), but our computed baseline slope (–2.56 °C/kPa) was greater than the previous baselines (–1.93 to –2.06 °C/kPa). We cannot determine why our line appears different, but any or all of the above cited factors could have influenced our results despite attempting to use comparable methods and equipment.

The seasonal course of the CWSI values for the irrigation treatments studied is shown in Fig. 2. Following an irrigation or rainfall event, water stress was usually relieved and CWSI declined accordingly. It also indicates the increase in the CWSI that occurred with time as available water in the soil profile decreased (Fig. 1). The CWSI values before DOY 180 may have been influenced by the warmer background soil despite efforts to "view" only foliage. Even with a fairly "wet" soil profile (i.e., like on DOY183 in Fig. 2), afternoon CWSI values can be large because the developing root system is still inadequate to permit the high instantaneous plant uptake rates to meet the large atmospheric evaporative demand at Bushland (Howell et al. 1986; Idso et al. 1982). The CWSI values changed from relatively low values (less than 0.2) to relatively high values quickly (in 2–3 days), particularly in hot

Fig. 2 Measured crop water stress index (CWSI) values during the 1992 season



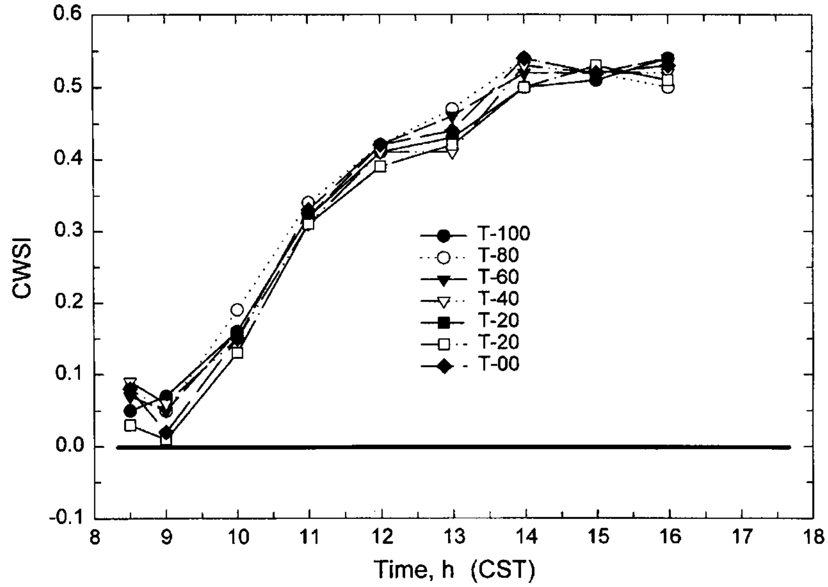


Fig. 3 Diurnal CWSI values measured on day of year (DOY) 183 in 1992

weather with strong wind speed conditions and even when the soil profile was relatively "wet." As Idso et al. (1982) demonstrated for cotton in Arizona, the crop's ability to match the environmental demand at a certain VPD or "potential" transpiration will depend on the extractable soil water in the root zone.

The CWSI values ranged from slightly below 0.0 in all treatments to maximum values of 0.52 in T-100 treatment; to 0.60 in T-80; 0.64 in T-60; 0.70 in T-40; 0.78 in T-20; and 0.87 in T-00 treatment plots. The seasonal mean CWSI values for each treatment calculated as the average of the CWSI values for different measurement periods during the growing season were 0.29, 0.32, 0.33, 0.38, 0.42, and 0.46 for the T-100, T-80, T-60, T-40, T-20, and T-00 treatments, respectively. Irrigations resulted in near full recovery from water stress in T-100 and T-80 treatments; however, only partial recovery occurred in the drier treatment plots. CWSI values in T-40, T-20, and T-00 treatments remained above 0.3 after DOY 181 (29 June). A sharp increase in CWSI values following DOY 181 in all the treatments was due to the larger air temperatures (T_{max} values of 37, 40, and 39 °C) and strong winds (wind speed values of 4.1, 4.5, and 7.1 m/s) encountered July 6–8. A rapid decline in CWSI values occurred on DOY 212 (30 July) in all treatments because of irrigation on DOY 207 followed by a rainfall of 30 mm on DOY 208 (26 July). A similar situation was observed on DOY 226 (13 August) in all plots, but recovery from water stress was partial in the drier treatments. For instance, CWSI value declined from 0.70 on DOY 223 (10 August) to 0.42 on DOY 226 in T-40; from 0.77 to 0.45 in T-20; and from 0.86 to 0.56 in T-00.

Trends in CWSI values are consistent in that the lowest water level (T-00) shows the highest stress level, and highest water level has the lowest stress (T-100). Soil water contents (Fig. 1) are consistent with the CWSI values (Fig. 2) in that the lowest irrigation levels (T-20 and T-00) had the largest soil water depletion levels and CWSI values while the higher irrigation levels (T-100 and T-80) had the smallest soil water depletion levels and CWSI values. CWSI values for the T-00, T-20, and T-40 treatments increased gradually toward the end of the growing season due to decreased soil water contents in the profile (Fig. 1). On DOY 195 and 212, T-100 had similar soil water contents (Fig. 1) but different CWSI values (Fig. 2); these were 0.2 CWSI and 0.03 CWSI, respectively). The weather conditions were similar, but DOY 195 was about 1.0 °C warmer and the wind speed was slightly higher.

Hourly CWSI measurements made on DOY 183 and DOY 227, respectively, for the six irrigation treatments are shown in Figs. 3, 4. The first measurement date was about 1 week after the beginning of growth stage 2 (8th visible leaf) [based on the modified Hanway scale from Ritchie et al. (1992)], while the second one was about 10 days before the growth stage 9 (kernels dented but moist). Maximum CWSI values occurred, in general, around 1500 hours to 1600 hours CST and reflected possible differences between the irrigation treatment (i.e., soil water contents) and the environment, previously mentioned above. The diurnal CWSI values on DOY 227 for T-00, T-20 and T-40 were consistently higher than for the rest of the treatments. The differences in CWSI values for the treatments were insignificant on DOY 183, but all were larger owing to the previously mentioned high evaporative demand (both VPD and wind were high).

Measurement of T_c alone may not provide adequate lead-time to satisfactorily manage a field-scale irrigation system. However, when IRT measurements are utilized in combination with a soil water balance method (either soil water measurement or ET modeling), it should be possible to schedule irrigations with a higher degree of confidence. The two methods together provided a needed cross-check to make sure neither gets too far afield. This would be desirable with LEPA irrigation, especially when irrigation capacity (flow rate per unit area) is smaller than optimum.

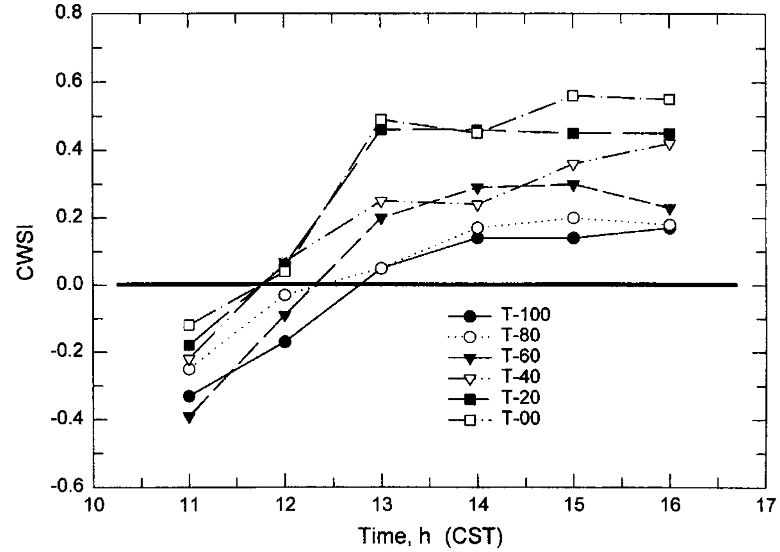


Fig. 4 Diurnal CWSI values measured on DOY 227 in 1992

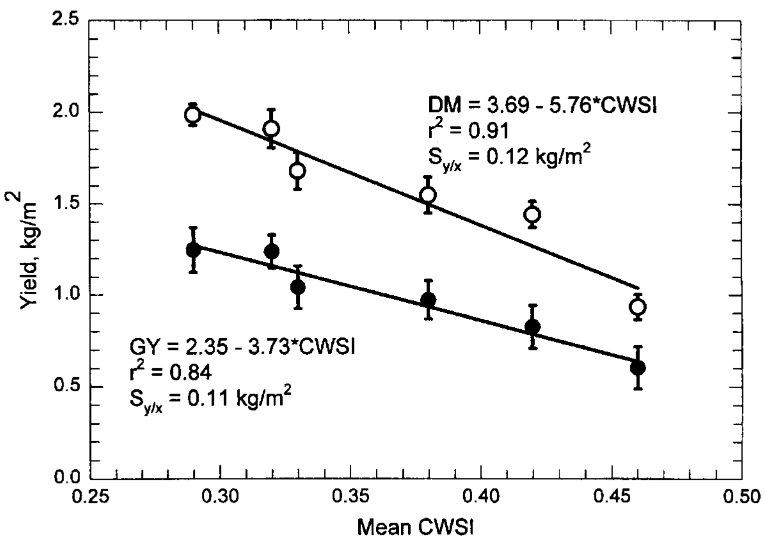


Fig. 5 Corn dry matter and grain yield relationships with mean seasonal CWSI. The *error bars* are ±1 SD

The relationships between dry matter and grain yields and seasonal mean CWSI values were basically linear (Fig. 5) within the range of mean CWSI values for this season. Although a linear relationship implies a slightly greater dry matter and grain yield for T-100 compared with T-80, neither the dry matter nor grain yields were statistically different (Table 3) between these two treatments. Table 3 and Fig. 5 show that the grain yields began to decrease to a significant extent when a mean CWSI value of 0.33 (T-60) was reached. The mean yields were not statistically different for a CWSI range from 0.33 (T-60) to 0.42 (T-20). The mean CWSI for T-60 was only 0.01 greater than that for treatment T-80 where the first significant yield decrease occurred. This implies that a "critical" CWSI value may occur near 0.32–0.33 when corn yields will begin decreasing with greater soil water deficit. These results agree with Nielsen and Gardner (1987) who reported a threshold CWSI value of 0.2 for corn. They also indicated that corn irrigated at CWSI values of 0.4 and 0.6 produced significantly lower yields than corn irrigated at CWSI values of 0.1 and 0.2. Steele et al. (1994) reported little difference between corn yields when irrigated at CWSI values of 0.2 and 0.4, but the yield did decline slightly (averaged 0.10 kg/m^2 lower) when irrigated at a CWSI value of 0.6. Stegman (1986) reported a 35% irrigation reduction and a 95% yield level when irrigations were timed based on a CWSI of 0.2. Keener and Kircher (1983) reported a greater linear correlation coefficient between corn yield and CWSI for a drier than normal year. Wanjura et al. (1990) reported similar yield-CWSI relations for cotton and sorghum. When they normalized the CWSI to their yield maximum, they showed that yield was insensitive when CWSI values were below about 0.3 and then a steeper yield decline as CWSI increased. Thus, the CWSI is a good indicator of plant response to available water, but it does not indicate the amount of water required to recover from water stress. Also, the mean CWSI appears limited in its ability to finely differentiate between small increments in

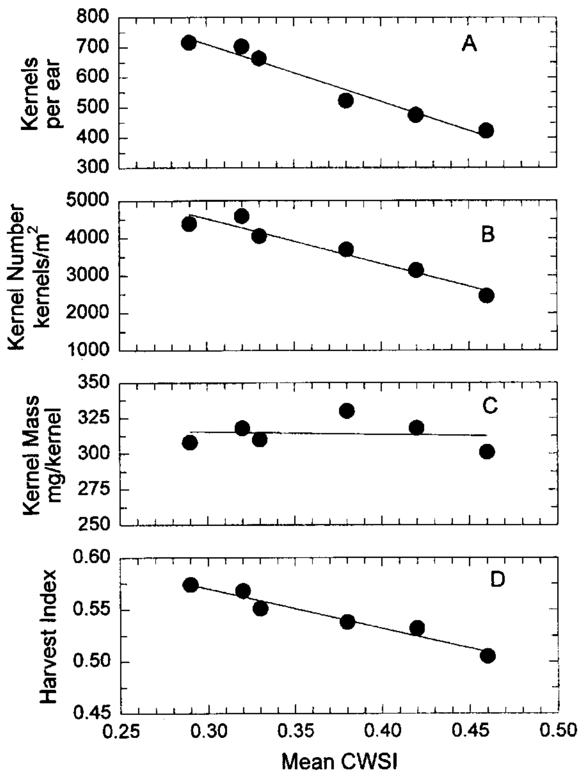


Fig. 6 Influence of crop water deficits depicted by mean CWSI on corn yield components of kernels per ear (**A**), kernel number (**B**), kernel mass (**C**), and harvest index (**D**) in 1992. The *lines* represent linear regression trend lines

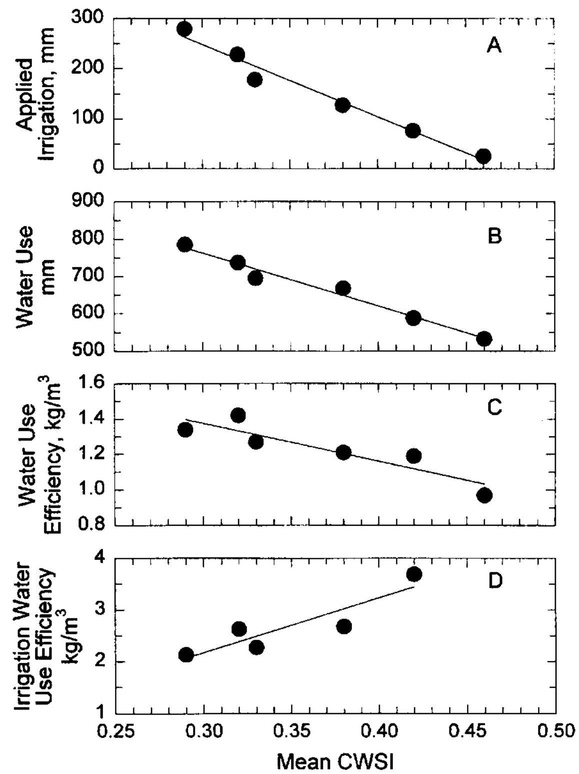


Fig. 7 Influence of crop water deficits depicted by mean CWSI on applied irrigation water (**A**), water use (**B**), water use efficiency (**C**), and irrigation water use efficiency (**D**). The *lines* represent linear regression trend lines

irrigation treatments like the ±20% water applications used here on this soil.

The corn yield component and harvest index data plotted in relation to the mean CWSI values are shown in Fig. 6. Linear trend lines (regressions) were drawn for illustration and not specifically to quantify functional relationships. Kernels per ear (Fig. 6A), kernel numbers (kernels per unit land area) (Fig. 6B), and harvest index (Fig. 6D) all declined with increasing CWSI values; however, harvest index was not statistically different (Table 3). Figure 6 shows that the difference in CWSI values between the T-80 (0.32 CWSI) and T-60 (0.33 CWSI) treatments were not large but did result in a statistically significant difference in the yield but not yield components. Kernel mass was relatively unaffected by the late water deficits that occurred in 1992. Keener and Kircher (1983) also reported a low correlation between kernel mass and CWSI, but they found a higher correlation between kernel number and CWSI similar to this study (Fig. 6C and 6B, respectively).

The irrigation, water use, and water use efficiency parameters in relation to the mean CWSI values are shown in Fig. 7. Baunsworth and Mack (1989) reported similar findings for sweet corn. Again, the linear trend lines (regressions) do not imply functional relationships, but they do aid the visual interpretation. Although the mean CWSI was closely coupled with the applied irrigation water and water use, it was not closely associated with water use efficiency. The IWUE was not strongly affected by the mean CWSI until a rather high irrigation deficit (T-20) was reached.

Conclusions

The CWSI offers an independent and direct measure of crop water status that can easily be used to supplement soil water measurements and/or crop water balance modeling either with crop growth or ET models to improve irrigation scheduling. This work determined a slightly different non-water-stressed baseline for corn from previous experiments that indicated a larger T_c-T_a difference (by −2 to −4 °C) for the same VPD in this environment. The CWSI was shown to respond to irrigation differences even in a year with above normal rainfall in a semiarid environment, but it could not easily differentiate small (±20%) irrigation differences.

In this experiment, the daily CWSI values followed soil water as would be expected. But the CWSI values seemed to be influenced to a larger extent by the environment (VPD, etc.) than might be expected for the soil water levels studied. The CWSI values responded to rainfall or irrigation predictably. Although not the explicit purpose of this work, it appears that together with past studies a CWSI value of 0.3–0.4 for corn might be a conservative timing parameter to avoid excess irrigations. Corn yields in this study were directly correlated with mean CWSI values. These correlations were related to the kernels per ear and kernel numbers, which were the crop yield components most affected by water deficits in this study. LEPA irrigated corn water use efficiency declined as CWSI increased, but for small to modest CWSI values, IWUE remained largely unaffected by water deficits.

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